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MAGNETIZATION AND THE GYROMAGNETIC RATIOS
OF THEIR MAGNETIC ELEMENTS.

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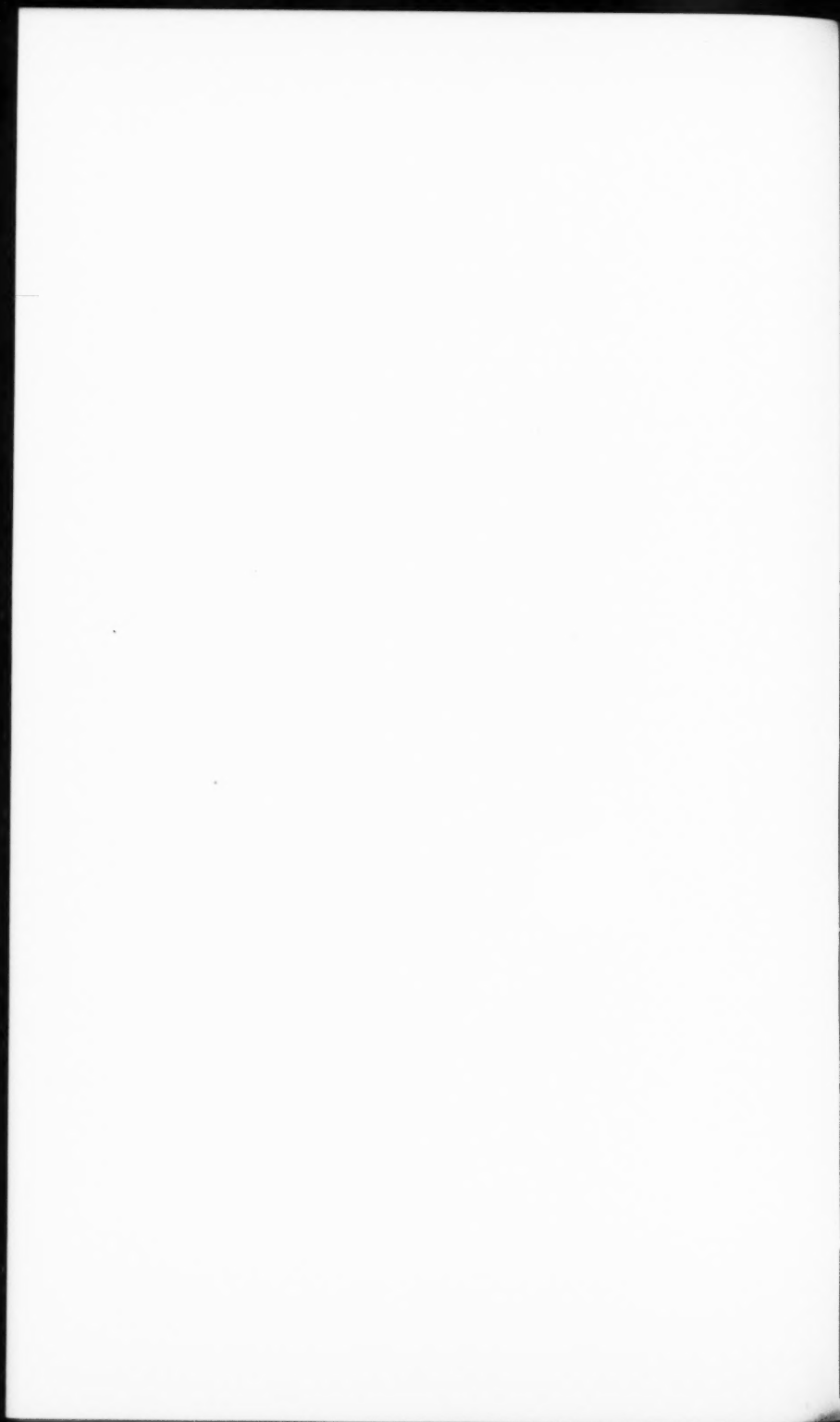


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1. INTRODUCTION. In an earlier paper in this journal (Vol. 66, No. 2, 1931, pp. 273-348) I have given an account of an elaborate investigation of the Einstein and de Haas effect (rotation by magnetization) in soft iron and permalloy. In this work the systematic errors were thoroughly studied and eliminated, and the gyromagnetic ratio for each of the two materials was determined with an error probably less than one-half per cent. The ratios found for iron and permalloy are close to $1.04 \times m/e$ and $1.05 \times m/e$, respectively. These are in agreement, within the experimental errors, with the values published in 1925 by L. J. H. Barnett and the author* as the result of an elaborate investigation on the magnetization of ferromagnetic substances by rotation, as well as with the value ($1.02 \times m/e$) obtained from the first investigation on iron when this effect was discovered in 1914.†

In connection with the early part of the investigation on the Einstein and de Haas effect in permalloy and iron published in 1931, experiments were made on nickel also, but the systematic disturbances proved so great that further work on this substance was abandoned until the methods should be thoroughly developed with the more tractable materials. In 1930 work on nickel was resumed. The present paper is devoted chiefly to work on this material and on cobalt.

2. METHODS OF EXPERIMENTATION. The principal work on nickel was done by the chief method described in the earlier paper, to which reference must be made for many of the details, and by a slight modification of this method. For the work on cobalt, and a part of the work on nickel, it was necessary to make some changes of importance, which will be described later (§ § 4, 5).

*S. J. Barnett and L. J. H. Barnett, *Proc. Amer. Acad. of Arts and Sciences*, 60, No. 2, 1925, pp. 125-216.

†See especially S. J. Barnett, *Phys. Rev.* 6, 1915, pp. 239-270.

The discussion of the new work will be facilitated by reference to Fig. 1, which is reproduced, with slight changes, from the earlier paper. The rod, or rotor, *F*, under investigation is axially suspended by a thin German silver wire or strip *D*. Hanging from the lower end of the rotor by a rigid joint is a brass rod *J* carrying parallel mirrors *I* on opposite sides, and, below, a group *L* of small permanent magnets

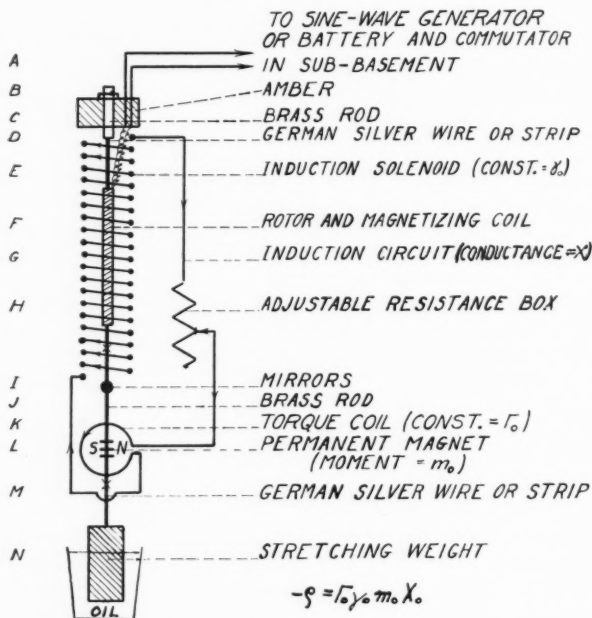


FIGURE 1. Diagram illustrating simplest experimental method.

(magnetic moment = m_0), all turned in the same direction. A heavy brass or copper weight *M* hangs from the lower end of the rod *J* on a second German silver suspension. The weight hangs in a vessel of light oil. Coils of wire surrounding the apparatus and traversed by suitable electric currents neutralize the intensity of the earth's magnetic field almost completely, when desired, in the region occupied by the rotor.

In all of the recent work and most of the earlier work, the magnetizing coil was wound directly upon the rotor F . This eliminates the possibility of certain important theoretical and experimental errors. From a storage battery and commutator, producing a flat-topped wave of electromotive force, current is led to the magnetizing coil by fine wires twisted together and wound into a single loose spiral around the suspension. (In the figure, the wires are shown separate for clearness.) The rotor is surrounded with a much longer uniformly wound cylindrical coil of wire, E , the *induction solenoid* (constant = γ_0); and the group L of small magnets is at the center of a small double coil, K , the *torque coil* (constant = Γ_0), the planes of whose turns are parallel to the magnets.

The coil E is connected in circuit with the torque coil K through an adjustable resistance box H , by which the conductance X of the circuit may be varied at will.

If the first harmonic of the magnetic moment of the rotor is $\mu = \mu_0 \sin \omega t$, the first harmonic of the gyromagnetic torque $-\rho \dot{\mu}$ will be $g = -\rho \omega \mu_0 \cos \omega t = G \cos \omega t$. The variation of μ induces an electromotive force $\psi = -\omega \mu_0 \gamma_0 \cos \omega t$ and a current $\psi X = -\omega \mu_0 \gamma_0 X \cos \omega t$ in the induction circuit. This current, traversing the torque coil, produces a torque $c = -\omega \mu_0 \gamma_0 X \Gamma_0 m_0 \cos \omega t = C \cos \omega t$ on the rotor system. The total impressed torque of frequency $\nu = \frac{\omega}{2\pi}$ on this

system is thus $(G + C) \cos \omega t$. The frequency ν of the first harmonic of the impressed electromotive force is, in general, made equal, or very nearly equal, to the natural frequency ν_0 of the vibrating system;* thus the amplitude of the vibration may be written $A = \beta (G + C)$, where β is a constant; or $A = \beta (G - C)$, if, as in practice, the torque coil is so connected in the circuit that c and g have opposite phases. In this case A vanishes for such a value X_0 of X that $G = C$; that is, when $\Gamma_0 \gamma_0 m_0 X_0 = -\rho$. The equation $A = \beta (G - C)$ may be written $A = \beta (G - \alpha X)$, the relation between A and C , or A and X , being linear, as shown in Fig. 2, curve G . The phase of the motion and of the torque change sign together when $X = X_0$; but if we consider only magnitudes, the relation between A and X is given by the two straight lines meeting at $X = X_0$ (corresponding to AF and FB of Fig. 3).

*The rotor will also resound for the impressed frequencies $\nu = 3\nu_0, 5\nu_0$, etc., but with continually diminishing amplitudes for a given amplitude of impressed electromotive force.

If there is an extraneous torque with amplitude Z in phase with g or in the opposite phase, the lines G will be replaced by the lines $G + Z$ or $G - Z$, meeting the axis of abscissae at $X_{0(z)} = X_0 + \delta X_0$ or at $X_{0(-z)} = X_0 - \delta X_0$. If such a torque is present, and its phase can be reversed without altering its amplitude, the true value of X_0 can thus be found by taking the mean of $X_{0(z)}$ and $X_{0(-z)}$.

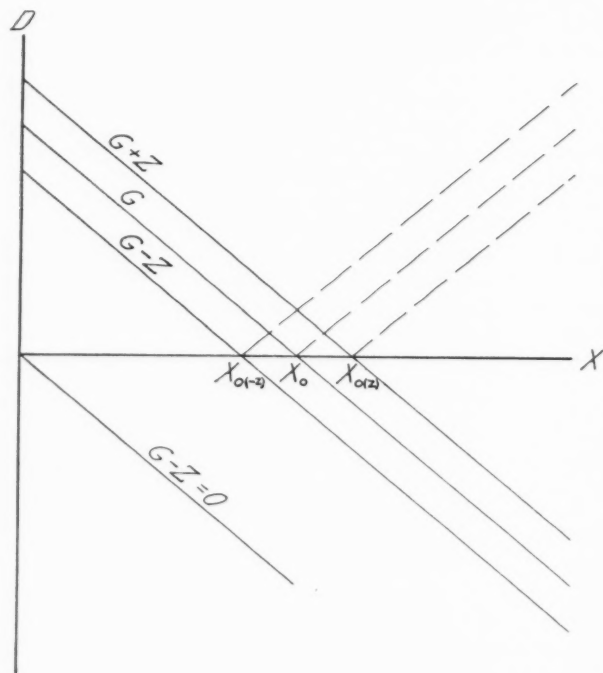


FIGURE 2. Vibration amplitude (D) versus conductance (X) with and without disturbing torques in phase with or in opposition to g .

If there is a torque in quadrature with g , the straight lines meeting at $X = X_0$ will be replaced by the symmetrical curved line CED , Fig. 3, with a minimum at $X = X_0$. Thus no systematic error is introduced by the presence of such a torque in determining X_0 , but

unless the minimum amplitude (EF) is small in comparison with that produced by g , the curve near the minimum will be so flat that X_0 cannot be determined with precision.

In the most important part of the earlier work $X_0 + \delta X_0$ and $X_0 - \delta X_0$ were determined by measuring *accurately* the amplitudes for $X = 0$, and $X = \text{approximately } 2 (X_0 \pm \delta X_0)$; and by measuring *approximately* the amplitudes A_0 for $X = X_0 \pm \delta X_0$; and inserting in the appropriate formula given in the earlier article. The same procedure was adopted for part of the work described here, but in

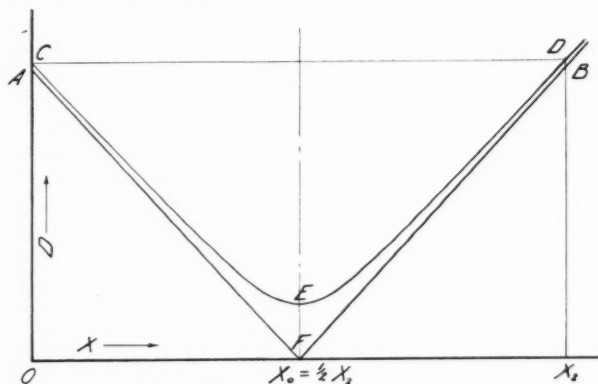


FIGURE 3. Vibration amplitude (D) versus conductance (X) with and without disturbing torque in quadrature with g .

much of this work $X_0 + \delta X_0$ was obtained by taking one-half the value of X for which the precisely measured amplitude (beyond the minimum) was *equal* to the amplitude (also measured with precision) for which $X = 0$. The first value was of course not observed directly, but was obtained by interpolation or extrapolation for values of X near $2 (X_0 + \delta X_0)$; and $X_0 - \delta X_0$ was obtained in a similar way.

3. ELIMINATION OF THE SYSTEMATIC ERRORS. Except for certain possible errors introduced on account of the modifications of apparatus made necessary by the peculiarities of some of the cobalt and nickel rotors, and discussed later in this paper, this subject has been fully treated in the earlier article. As shown there, all the incalculable systematic errors which had been discovered can be eliminated by three processes, as follows: (1) by reducing to zero, or approxi-

mately zero, the three components of the intensity of the earth's magnetic field; (2) by making observations with the suspended system first in one azimuth and again when turned about the vertical through a half revolution; and (3) by making observations with the commutator (or generator) connected to the magnetizing coil in one way, and then with the connections reversed.

Among earlier investigators only two, J. Q. Stewart* and G. Arvidsson,† have taken the precaution of annulling the vertical part of the earth's intensity; and only one, J. Q. Stewart, has deliberately sought to eliminate what he suspected might be an error due to magnetostriction by adopting the equivalent, in his work, of process (3). This process is necessary to eliminate the effects of inequality in the half cycles of current and magnetization, especially when the magnetizing coil is not wound on the rotor. Even in the cases of permalloy and iron all the processes mentioned are necessary.

The sort of error which may be made in the case of nickel by failing to compensate the vertical intensity is indicated in Fig. 4, which exhibits curves drawn between the vibration amplitude and the current in the coil which was used to neutralize the vertical part of the earth's intensity. The resistance of the induction circuit was made approximately equal to that for which zero amplitude would be obtained if only the gyromagnetic torque were present. If this were the case, the amplitude would be zero, or nearly zero for a current 0.95 ampere in the coil which compensated the vertical intensity, and independently of the magnitude of the current in the magnetizing coil. As the figure shows, the position of the minimum depends in a marked degree upon the current; and for neither of the currents tried does it occur for zero vertical intensity. It was on account of such results as this that work on nickel was postponed until more tractable substances had been investigated.

The disturbing torques due to inequality of half cycles—in spite of great pains taken to make them equal—often have components in phase with (or in opposition to) g with amplitudes which are quite comparable with—and may even be equal to or greater than— G itself. The lines G in Fig. 2 are then replaced by such lines as those marked $G - Z$, $G + Z$, or $G - Z = 0$.

For example, the very difficult rotor Iron C (see § 9, footnote) in one set of observations gave the (uncorrected) values of $\rho \times e/m$ exhibited in Table I.

*J. Q. Stewart, *Phys. Rev.* 11, 1918, p. 100.

†G. Arvidsson, *Phys. Zeit.* 21, 1920, p. 88.

TABLE I.

Position of magnetizing switch	Direct		Reversed	
Azimuth	NPW	NPE	NPW	NPE
$\rho \times e/m$	1.201	1.223	0.917	0.938
Means of $\rho \times e/m$	1.212 (1.070)		0.928	

This is by no means an extreme case for this rotor. Of course, the grater Z in comparison with G , the less reliable is the final mean

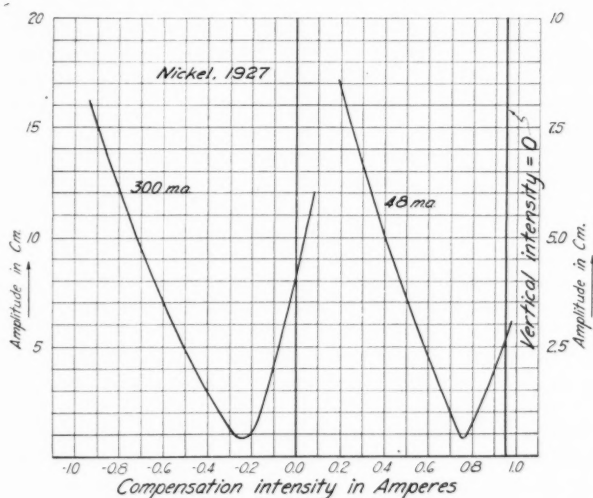


FIGURE 4. Effect of disturbing torques on nickel rotor with vertical intensity of earth's field compensated and uncompensated.

likely to be, as it is not certain that conditions will remain constant throughout the changes needed for the elimination of the effect of Z .

Curves like $G - Z$, $G + Z$, etc. can be obtained with any rotor at will by covering a part of one of the commutator segments with a piece of gummed paper or other insulator. In this way, in the earlier work, it was experimentally proved that the effects of cycle inequality could be eliminated by reversing the magnetizing current switch or by

making an equivalent change. Thus in the case of sine waves the elimination could be made by reversing the generator field. As an example of this latter method some experiments made on the excellent rotor FeI_2 , described in the earlier article, may be cited. These (comparatively rough) experiments were made with the rotor in only one azimuth, there being little difference between results obtained with the two. With the commutator segments equal, the value of $\rho \times e/m$ (uncorrected) was 1.06. When the front of one segment was cut off 1.3 cm. (about 8 or 9 percent) by a strip of gummed paper, the value for one direction of the field was 1.14, for the other 0.96; mean, 1.05. Had it not been for the excellent characteristics of this rotor the difference produced by this large departure from half-cycle equality would have been far greater. For some of our rotors it would undoubtedly have given a positive apparent value of $\rho \times e/m$ for one direction of the field (or switch), and a negative apparent value for the other.

It is only recently that the existence of these torques has been recognized by others, whose experiments on this account have been vitiated by errors of a serious character. In a recent paper Coetier and Scherrer* have stated that the extraneous torque of this kind due to the action of the magnetizing coil (when fixed to the earth) on the rotor is in quadrature with g . This is true of the primary magnetic torque only, but by no means true of the actual effective torque on the rotor, which results from the primary torque and the torque due to the suspension displacement together. We have abundant evidence in addition to that quoted above that the in-phase or in-opposition component of the torque may be very large indeed.

4. METHOD OF REDUCING THE TORQUE DUE TO MAGNETO-STRIC-TION. When the method of experimentation which had been developed to such a degree of perfection as to yield precise results with permalloy and soft iron was first applied to a cobalt rotor, the disturbing torques were so great as to mask entirely the gyromagnetic torque. As it was probable that magneto-striction was one of the chief sources of the trouble, the construction of the rotor was modified as indicated in Fig. 5. The magnetic rod was mounted coaxially inside a brass tube of somewhat greater length. Three small brass rings with internal diameter just greater than the diameter of the rod, and external diameter just less than the internal diameter of the tube, were soldered around the rod, coaxially, at the center and ends. The

* *Helvetica Physica Acta* 5, 1932, p. 217.

central ring was soldered to the tube also. The center of the rod was thus fastened rigidly to the tube, while the ends were free to slide longitudinally in the tube. The magnetizing coil was wound on the brass tube. This type of construction was adopted with the hope

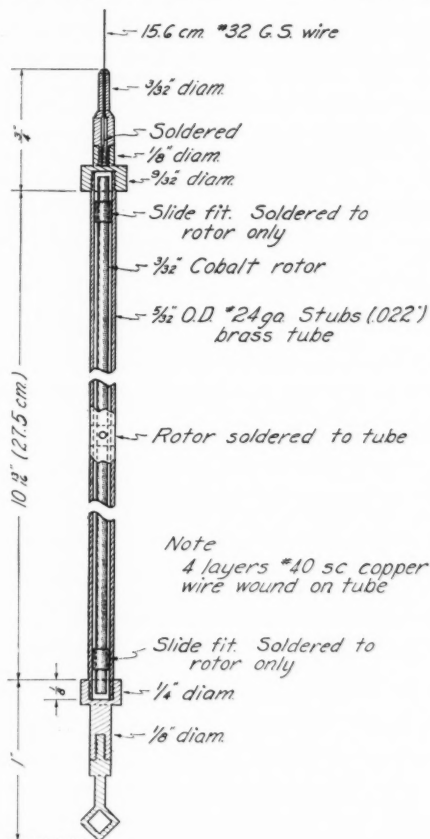


FIGURE 5. Complex rotor designed to eliminate effect of magnetostriction. The new type of head with suspension terminating in spiral soldered in place was used only with Iron C.

that when the magnetostrictive oscillations occurred, the center of mass of the rod would remain fixed and the disturbance would not be communicated to the brass tube and suspension.

The changes greatly improved the behavior of the cobalt, but the disturbing torques were still large. The in-phase component could be corrected for by the process of reversal described above, but the quadrature component was usually too great for any precision.

5. METHOD OF REDUCING THE QUADRATURE TORQUE. It thus became necessary to add a device to annul this quadrature component. The torque coil formerly used was replaced by a pair of coils *F* and *G*, Fig. 6, as nearly alike as practicable, and wound twin. A second

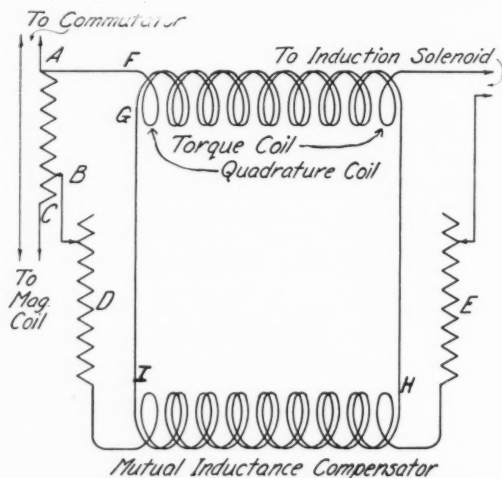


FIGURE 6. Arrangement for compensating quadrature torques.

pair *H* and *I*, also wound twin and as nearly like *F* and *G* as practicable, was constructed. *F* and *G* were mounted in the position of the coil formerly used, and *H* and *I* were mounted at a distance. *G* and *I* were connected in series in the induction circuit, while *F* and *H* were connected in series through an adjustable high resistance box *D*, either directly to the terminals of the commutator, or, as was nearly always the case, to a non-inductive variable rheostat *AC* in series with the magnetizing coil. The two sets of coils were so connected

that the mutual inductance between FH and GI was zero or very small.

A small variator, one of whose two coils was connected in each circuit, made it possible to neutralize the mutual inductance exactly; but this was unnecessary.

With the rectangular waves used the electromotive force between the terminals of the commutator and the magnetizing current were very nearly in phase with one another and in quadrature with the gyromagnetic torque. Thus the current in the coils FH , and, therefore, the torque exerted by F on the vibrator magnet, were very nearly in quadrature with the gyromagnetic torque. By altering the resistance D in series with FH , or the resistance of the conductor AB across which the leads were shunted, and by interchanging the leads if necessary, it was thus possible to reduce any quadrature torque present to a very small quantity.

6. SYSTEMATIC ERRORS DUE TO THE QUADRATURE COIL. The adoption of this arrangement introduces three possible new sources of systematic error. In the first place, the current in FH may not be *exactly* in quadrature with the gyromagnetic torque g . In this case a torque in phase with g (or in opposition) must result from the direct action of F on the vibrator magnet. The constants of the circuits and the method of experimentation (with flat-topped waves) insure, however, that such a torque cannot in any case exceed a small fraction of the quadrature torque, and, in general, a smaller fraction of g . The effect of any such residual torque, moreover, would be completely eliminated in each half set of observations if the current in the quadrature coil were made identical for both directions of the switch controlling the magnetizing current, since the resistance AC (Fig. 6) is in series with the magnetizing coil, and thus the connections of both to the commutator are reversed together. In the actual work this elimination is not made completely, because the quadrature current is given different values for the two directions of the switch. This is necessary or desirable because there are in general other quadrature torques in addition to those due to the half-cycle inequalities.

In the second place, when the mutual inductance M between FH and GI is not zero, the current in the quadrature coil will induce in the induction circuit a current nearly in phase with (or in opposition to) the gyromagnetic torque g . If I is the amplitude of the current in the quadrature coil F , the amplitude of the current induced in GI will be $MI\omega/R$, where $\omega = 2\pi \times$ the frequency and R is the resistance

of the induction circuit. The ratio of the amplitude of the in-phase (or in-opposition) torque thus produced by the quadrature coil to the amplitude of the quadrature torque itself, since F and G have practically the same constant Γ , is $M\omega/R$. This would be entirely negligible even if the mutual inductance between F and G were not almost completely neutralized by that between H and I , M being thus made nearly zero.

In the third place, the effect of the presence of the quadrature circuit, which always has a high resistance, is to diminish slightly the (already negligible) inductance of the induction circuit (containing GI), and to increase slightly its resistance from R to $R + \delta R$. If

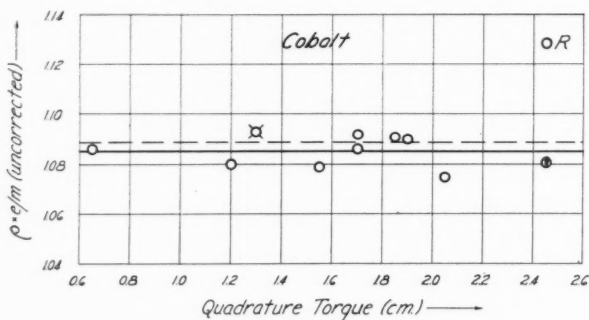


FIGURE 7. Apparent gyromagnetic ratio *versus* quadrature torque (Cobalt IV). The point marked R was rejected for the solid line, and retained for the broken line.

the value of R (or $X = 1/R$) uncorrected for this effect were used in the formula for calculating ρ , the value of ρ obtained would be too great by the fraction $\delta R/R$. It is easy to show that with the constants of the circuits used in this work $\delta R/R$ would be entirely negligible even if the mutual inductance between F and G were not compensated at all by that between H and I ; and $\delta R/R$ is proportional to the mutual inductance M , which, because of the compensation, all but vanishes.

The first mentioned of these three torques is thus the only one which could possibly produce any appreciable error in the work described here. That it also was too small a fraction of g to be detected (and that all three together were too small to be detected) is proved by Fig. 7, in which the calculated values of the gyromagnetic ratio

(uncorrected for coil moment and electron inertia) for the rotor Cobalt IV is plotted as a function of the original quadrature torque acting when the resistance of FH was made infinite. This torque is expressed in terms of the mean minimum amplitude of the vibration on the vibration-amplitude *versus* conductance curve. It is evident from the curve that if there is any in-phase (or in-opposition) component present, it is too small to produce an appreciable effect on the determination of ρ . If the in-phase or in-opposition torque were appreciable, it could be eliminated by extrapolating to zero residual amplitude. Fig. 8 gives a chart constructed in the same way for the rotor Nickel III.

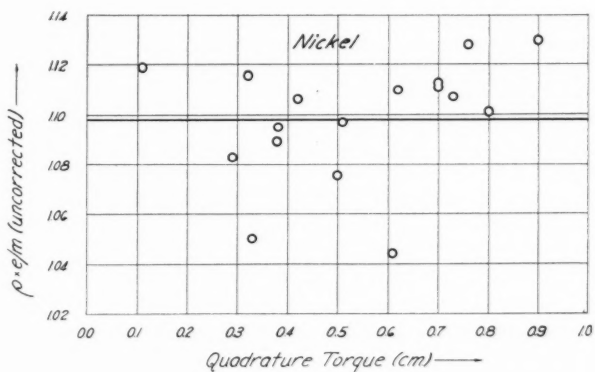


FIGURE 8. Apparent gyromagnetic ratio *versus* quadrature torque (Nickel III).

7. THE NICKEL ROTORS. Successful observations on the gyro-magnetic ratio were made with three nickel rotors, two of them similar in general construction to the standard rotors of permalloy and iron and of the same length. The first, Nickel I, was $5/64$ inch in diameter and was wound with 4 layers of *SC* No. 40 copper wire. For a current of 100 m.a. in the coil its magnetic moment was 649 e.m.u. The moment of the magnetizing coil alone was about 4.5 e.m.u.

The second rotor, Nickel II, was $1/16$ inch in diameter, and was wound in the same way. Its magnetic moment, for a current of 100 m.a., was 232 e.m.u.; and the moment of its coil, for the same current, was about 2.2 e.m.u.

The third rotor, Nickel III, was of the more complex type described in § 4. The length of the rotor was about equal to that of the others. The diameter of the magnetic material was $5/64$ inch, and the outer diameter of the brass tube was $5/32$ inch (4.0 mm.) The brass tube was wound with four layers of No. 40 SC copper wire. Its magnetic moment for a current of 100 m.a. was 360 e.m.u. The moment of the coil alone was about 12 e.m.u.

All the magnetic material was annealed.

8. OBSERVATIONS AND RESULTS FOR NICKEL. Five groups of observations were made on the three nickel rotors, and the results are given in Table II. Some of the observations were made like the

TABLE II.

The Gyromagnetic Ratio for Nickel.

1	2	3	4	5	6	7	8
Group	Rotor	Sets	Frequency	Correction	Range	Gyromagnetic Ratio	Approximate Mean Amplitude
I	Ni I	11	10/sec	$m/e \times$ -0.006	$m/e \times$ 0.023	$m/e \times$ 1.045 ± 0.005	2.5 cm.
II	Ni I	11	10	-0.006	0.015	1.074 ± 0.003	2 cm.
III	Ni II	6	12.8	-0.009	0.088	1.050 ± 0.033	3 cm.
IV	Ni I	15	10.3	-0.006	0.014	1.059 ± 0.003	6 cm.
V	Ni III	17	5.44	-0.031	0.086	1.067 ± 0.018	2 cm.

last series described in the earlier paper (See Table 51-1, p. 343); but in the modification of the method used in much of the work observations had to be made for two values of the resistance of the induction circuit (in addition to ∞) in order to interpolate for equal amplitudes. This of course increased the time necessary for a complete set of observations considerably. The frequencies of the rotors in the brass tubes were so low, and the time necessary for the amplitudes to reach their steady values so large, that with these rotors a period of over seven hours was required for one complete set (including the preliminary and final measurements of compensating currents, etc.).

In Table II, column 1 gives the order in which the different groups of observations were made; column 2, the designation of the rotor; column 3, the number of complete sets in the group; column 4, the

frequency; column 5, the correction to the observed value of the gyromagnetic ratio due to the moment of the magnetizing coil and to electron inertia, combined, which were not otherwise taken account of in the calculations; column 6, the range over which the gyromagnetic ratio fluctuated in the group; column 7, the mean value of the gyromagnetic ratio and its mean error; and column 8, the approximate mean vibration amplitude.

The results for Group I, in spite of the small average error, are somewhat uncertain on account of the fact that the moment of the vibrator magnet was not so well known as it usually was; but the uncertainty in the moment was by no means so great as the discrepancy between the results of I and those of some of the other groups. The results of Group II on the same rotor are considerably superior. Through an accident, the fundamental frequency of the electromotive force applied to the rotor in both these groups was made three times the natural frequency of the rotor, which accounts for the small amplitudes obtained. See §2, foot-note.

Group IV, on the same rotor, is considered far more reliable than either I or II. The mean result for I and II, viz. 1.060, is almost identical with the result of IV.

The mean error for Group III, on Nickel II, is much greater than that for any of the other groups. In spite of great pains taken in its construction, this rotor was exceedingly difficult to work with, doubtless on account of asymmetry. The extraneous torques, both in-phase and in-quadrature, were large, and the results are considered less reliable than those of any other group.

The mean value of $\rho \times e/m$ from Group IV, viz. 1.059, agrees closely with the (much less precise) mean from all the other groups, viz. 1.057, and is probably correct within less than 1 per cent. Comparatively little weight should be attached to the smaller value of Group III.

9. ROTORS OF COBALT. Four cobalt rotors were constructed, all of them from material presented by the Bell Telephone Laboratories. This consisted of 92.4 percent cobalt, 4.2 percent copper, 1.5 percent iron, and 1.8 percent nickel. The copper was added to make the material less difficult to work. Three of them were made like the simple wound rotors previously described. Of these three rotors, one was $3/32$ inch in diameter and annealed, another was $1/8$ inch in diameter and annealed, while the third was $3/32$ inch in diameter and was not annealed. All were wound with 4 layers of No. 40 SC copper wire. For the reason given above it was impossible to secure satisfactory determinations of the gyromagnetic ratio with any of

these rotors. A fourth rotor, designated here as Cobalt IV, of the same material, 3/32 inch in diameter and annealed, was constructed like the complex nickel rotor Nickel III already described. The coil was almost exactly similar to that of Nickel III. The moment for a current of 100 m.a. in the coil was 1138 e.m.u. In spite of many efforts I have not yet succeeded in getting suitable material for the construction of rotors of pure cobalt.*

TABLE III.
The Gyromagnetic Ratio for Cobalt.

1	2	3	4	5	6	7	8
Group	Rotor	Sets	Frequency	Correction	Range	Gyro-magnetic ratio	Approximate Mean Amplitude
I	Co IV	13	5.52/Sec.	$m/e \times -0.010$	$m/e \times 0.054$	$m/e \times 1.081 \pm 0.009$	4.5 cm.
I'	Co IV	12	5.52/Sec.	-0.010	0.018	1.077 ± 0.006	4.5 cm.

10. OBSERVATIONS AND RESULTS FOR COBALT. The results of the observations made with the quadrature torque compensated are given in Table III, constructed like Table II.

**Complex rotor of iron.* Another rotor, of iron, designated as Iron C, was made in the same way of some material kindly furnished by Professor Honda, whose description has not yet reached me. It was 5/64 inch in diameter and was turned down from a thicker rod composed of several single crystals. It was then carefully annealed. This rotor was exceedingly difficult to work with, the in-phase and quadrature disturbing torques being both very large and more or less variable. For reasons which are not understood, the lower end of the suspension repeatedly pulled out of the rotor, causing the magnet-mirror system to fall. This difficulty was remedied by remodeling the rotor cap and method of attachment of the suspension as shown in Fig. 5, the lower end of the suspension being coiled up and soldered inside the cap. With other rotors also we have sometimes been troubled with the pulling out of the lower end of the suspension, in spite of great pains to prevent it, and have suspected this due to magneto-striction, whose effects do not vanish even in the complex rotors. The mean value of $\rho/m/e$ obtained with this iron rotor is 1.048; but relatively little weight is to be attached to this result, as the observations, in spite of great care and much labor, are far inferior to those obtained earlier with Armco iron. (See § 3 above for remarks on the magneto-strictive effects with this rotor.)

As the table shows, thirteen complete sets of observations were obtained with Cobalt IV giving for $\rho/m/c$ the mean value 1.081 ± 0.009 . The first set of observations, obtained when the new type of rotor was used for the first time, gave a result much greater than any of the others, as indicated by the point marked *R* in Fig. 7. If this observation is rejected the result is 1.077 ± 0.006 . This value is probably correct within 1 percent.

11. GENERAL CONCLUSIONS. While the results obtained in this investigation on cobalt and nickel are not so precise as those obtained on permalloy and soft iron, they are believed far more reliable than any other results hitherto published by others on rotation by magnetization, or the Einstein and de Haas effect, on account of the more nearly complete elimination of the systematic errors.

Like the results on permalloy and soft iron in the author's earlier paper on rotation by magnetization, the results given here are in complete accord, within the limits of the experimental errors, with those obtained by L. J. H. Barnett and the author in their work on magnetization by rotation. In that work the mean value of ρ for all the ferromagnetic substances investigated was $1.059 \times m/c$. In the present work, on the converse effect, the mean value for iron (1.037), permalloy (1.049), nickel (1.059), and cobalt (1.077) is $1.055_5 \times m/c$. The agreement is remarkable in view of the fact that many serious systematic errors had to be eliminated in each investigation, and the fact that the errors were of entirely different kinds in the two researches.

12. SPECIAL ACKNOWLEDGMENTS. While this paper is a sequel to the 1931 paper referred to in § 1 and elsewhere above, the new work overlaps the older to a considerable extent, and I must again express my obligations to the assistants mentioned when the earlier work was published. In addition I desire to thank Dr. Vaino Hoover who has helped me in the more recent part of the work. I have continued to be greatly indebted to the Carnegie Institution of Washington for the use of equipment, and to the Board of Research of the University of California and to the California Institute for their support. To the late Dr. H. D. Arnold, and the Bell Telephone Laboratories, I am again indebted for material; and for other material I have to thank Professor Honda. The experimental work has been done in the Norman Bridge Laboratory of the Institute.

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